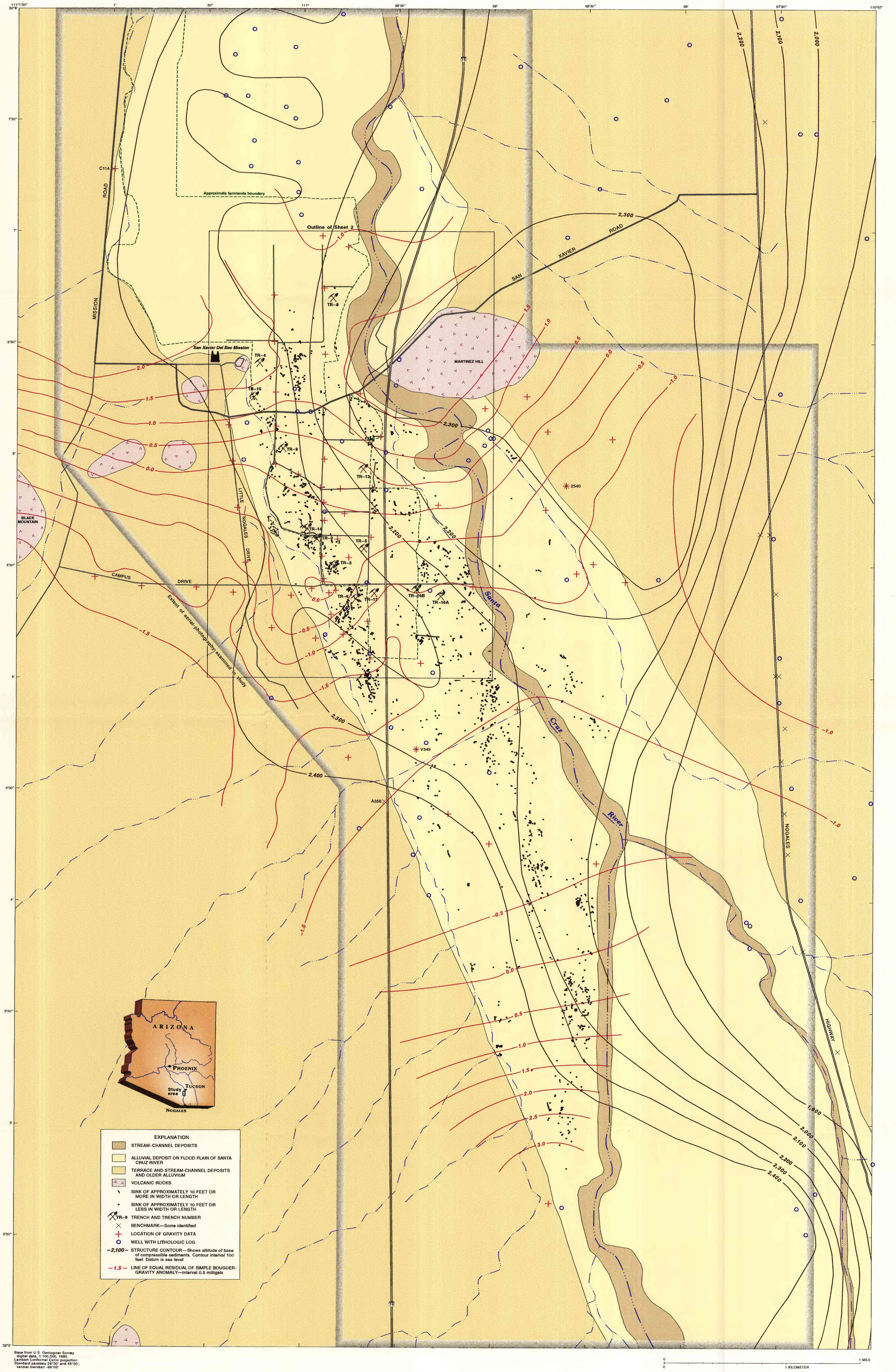
PREPARED IN COOPERATION WITH THE
BUREAU OF RECLAMATION
and the
TOHONO O'ODHAM NATION



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INTRODUCTION

Land subsidence in the form of sinks and depressions has occurred on and near the farmlands of the San Xavier District of the Tohono O'odham Nation in Pima County near Tucson, Arizona. The sinks occur in alluvial deposits along the flood plain of the Santa Cruz River in the Tucson Basin. Sinks on and near the farmlands were first described near the turn of the century and also were noted during construction of Interstate 19 in the 1960's (Arizona State Highway Department, written commun., 1995). The sinks increased in number and size and became a hinderance to farming activities in the mid-1980's. Formation of sinks on the farmlands has apparently accelerated since the mid-1980's and has damaged the irrigation system and some fields. Sinks also have been reported immediately north of the San Xavier District on the flood plain of the Santa Cruz River. This investigation was undertaken by the U.S. Geological Survey, in cooperation with the San Xavier District, Tohono O'odham Nation and the Bureau of Reclamation (BOR), to determine the causes of the sinks. Possible mechanisms for the formation of sinks include several types of compaction and erosion of near-surface material.

Methods

Several methods were used in the investigation to help determine whether the sinks are a result of aquifer-system compaction or several types of near-surface processes. Aquifer-system compaction was evaluated by mapping the distribution of compressible materials in the local aquifer system, measuring land subsidence at benchmarks, and relating water-level changes to the formation of sinks. Detailed mapping of the distribution and morphology of the sinks was essential for evaluating their causes. Near-surface processes were evaluated through inspection of near-surface materials in trenches and laboratory analyses of soil samples from the trenches. Electromagnetic induction and ground-penetrating radar methods were used to evaluate their ability to identify areas that have potential for sink development and to detect subsurface voids.

Drillers' logs, geophysical well logs, and geologic logs were used to determine the distribution of compressible sediments in the local aquifer system. Gravity surveys were used to map the local geologic structure. The altitude of several benchmarks were resurveyed along a profile east of the farmlands and in the sink areas. Water-level declines were determined through a review of historical and current water-level data.

Distribution and morphology of sinks were mapped by stereoscopic viewing of high-resolution aerial photographs at a scale of about 1:2,500 that were taken in December 1995 and February 1996. Locations of sinkholes were digitized to produce a geographic-information system (GIS) coverage. Horizontal control was provided by surveying the positions of several features on photographs using the global-positioning system (GPS). Many sinks were verified by field observations.

Thirteen trenches were excavated to depths of 13 to 19 ft. Trenches were inspected visually for soil characteristics, vertical extent of sinks, and possible conduits for the transport of water and sediment, which could have included voids, root casts, cracks, joints, burrows, and gravel layers. In-place density determinations were made in selected soil layers at several trenches. Laboratory analyses of samples collected from the trenches included particle-size distribution, moisture content, Atterberg limits, organic content, and clay mineralogy. Geologic logs from previous boreholes and trenches in the area were reviewed to compare with observations of trenches dug in this study.

Shallow electromagnetic surveys were made using EM31-D and EM34-3 instruments to determine the relation of electrical conductivity of the upper 100 ft of sediments and the distribution of sinks. The electrical conductivity of the subsurface is controlled by the sediment's grain size, mineralogy, clay content, orientation, porosity, moisture content, and water conductivity.

HYDROGEOLOGY

The Tucson Basin is a north- to northwestward-trending alluvial basin bounded by mountains of igneous, metamorphic, and sedimentary rocks (Reynolds, 1988; Davidson, 1973). Volcanic rocks crop out in the study area at Black Mountain and Martinez Hill. The valley floor is underlain by unconsolidated to indurated alluvial deposits with interbedded volcanic rocks. The three main sedimentary units underlying the valley floor are the Pantano Formation of Oligocene age, the Tinaja beds of Miocene to Pliocene age, and the Fort Lowell Formation of Pleistocene age. These units vary lithologically from well-cemented conglomerate to unconsolidated gravel, sand, silt, clay, and mudstone. Clay content generally increases with depth from the Fort Lowell Formation to the Tinaja beds. The combined thickness of the three units ranges from several tens to hundreds of feet near the basin boundaries to more than 10,000 ft near the basin center (Eberly and Stanley, 1978). Recent unconsolidated stream and flood-plain deposits (Davidson, 1973) overlie the three main sedimentary units and generally are less than 50 ft thick.

The regional aquifer system in the Tucson Basin comprises the Pantano Formation, the lower and upper Tinaja beds, and the Fort Lowell Formation. The most permeable and compressible part of the aquifer system comprises the upper Tinaja beds and Fort Lowell Formation (Anderson, 1988). Unconsolidated alluvial deposits along the Santa Cruz River also were part of the upper part of the aquifer system before recent water-level declines.

Water-Level Declines and Aquifer-System Compaction

Ground-water conditions in the study area have changed greatly since the late 1800's. The water table was near the land surface along the flood plain of the Santa Cruz River in the study area before extensive ground-water pumping. Ground water generally flowed to the north and discharged to the perennial Santa Cruz River and to springs in the adjacent wetlands (Betancourt, 1990). Incision by the river and extensive ground-water withdrawals have resulted in water-level declines and changes in ground-water flow directions. In the present ground-water flow system, recharge generally occurs from infiltration of ephemeral runoff in washes including the Santa Cruz River channel and along the flood plain from infiltration of excess irrigation water. Ground water flows toward withdrawal points at irrigation wells in the area of the farmlands and municipal-supply wells north and east of the study area.

Water levels in the study area declined from near the land surface to about 33 ft below the land surface by the early 1950's. The rate of decline increased to about 3 ft/yr from about 1960 through the 1970's and decreased in the 1980's and 1990's. Water-level declines since about 1960 ranged from 22 to 84 ft on the farmlands and were a maximum of 162 ft at a well 7 mi south of the farmlands. Depths to water in the study area currently range from 100 to 197 ft below the land surface.

Land subsidence near the farmlands has been caused by a declining water table and inelastic compaction of silt and clay layers (Schumann and Poland, 1970; Anderson, 1988; Hanson, 1989; and Schumann and Anderson,1989). Subsidence of 2 to 6 in. has been measured between 1953 and 1994 at benchmarks about 2 mi east of the farmlands along Nogales Highway. Maximum subsidence corresponds to a gravity and structural low that contains the greatest thickness of compressible sediments. About 4 in. of subsidence occurred between 1953 and 1980 (Anderson, 1988). The measurements include those from a benchmark near an extensometer where water levels and aquifer-system compaction have been monitored since 1979. Compaction measured at the extensometer in the upper 761 ft of sediments, including 643 ft of saturated sediments, has been less than 1 in. since 1980.

No measurable subsidence was detected at four bench marks near the farmlands in fall 1995 and winter 1996 using differential GPS techniques. The recently surveyed altitudes of bench marks 2540 and C114 were about 2 in. above the altitudes surveyed in 1976 and 1935, respectively. The apparent increase in altitude at the bench marks probably resulted from the use of different datums for the initial and repeat surveys. The altitudes of bench marks V349 and A358, about 2.5 mi south of Martinez Hill, were within 1 in. of the altitudes surveyed in 1960. A bedrock bench mark from outside the study area used in the 1960 survey also was used in the repeat survey.

Land subsidence is evident south of the farmlands at a well with a concrete pad elevated by about 4 in. above the land surface and at nearby bench mark V349, which is protruding a few inches more above the land surface than when it was installed in 1960. Surface erosion does not appear to be a cause of the altitude changes. The area has the potential for aquifer compaction because it is on the flood plain and near the structural and gravity low immediately west of the area of maximum subsidence on Nogales Highway. The elevated well pad and bench mark and the lack of measurable subsidence indicate compaction probably has occurred in the upper 10 ft of sediments above the bottom of the bench mark and well-casing construction. Unfortunately, the well-casing depth and depth to the bottom of the bench mark are unknown. The depth of the bench mark probably is greater than 10 ft.

Subsidence on the farmlands could not be measured owing to the lack of bench marks. Data from additional bench marks would improve knowledge of the distribution and magnitude of subsidence and compaction in areas that the current measurements are unable to quantify.

DESCRIPTION OF SINKS

More than 1,700 sinks were mapped, and their morphology was described using stereo-pair aerial photographs. Field verification indicated that although some sinkholes as small as a few inches in diameter were visible on the aerial photographs, many other small ones were not visible. The scale of the photographs allowed the shape of sinks larger than about 10 ft to be described and digitized. Those smaller than about 10 ft were digitized as point features.

Distribution

Sinks occur from near the San Xavier Mission to about 4 mi south of the mission and from about Little Nogales Drive to about 1 mi east of the Santa Cruz River. Sinks are confined to the flood plain of the Santa Cruz River and are most abundant near the farmlands but occur in both irrigated and nonirrigated areas. The most striking features of the sink distribution are the patterns of densely spaced sinks and sink-free zones that parallel the river channel and a major channel on the west edge of the flood plain. The density of sink distribution is greatest along a north- to northwestward trending 1,500-foot-wide band that parallels the western boundary of the flood plain for about 2 mi from near San Xavier Road to Interstate 19 and includes the farmlands. Many areas on the farmlands with the greatest density of sinks and coalesced sinks are near irrigation structures. Other areas of high-sink density occur along a band that parallels the river channel and lies within about 0.5 mi of the channel. A 1,500- to 3,000-foot-wide band that is nearly free of sinks separates the two prominent bands. No apparent relation exists between sink size and location relative to the river. A few sinks occur east of the river channel from 0.5 to 2 mi south of Martinez Hill.

Morphology

Sinks range in shape from circular to linear and range in depth from shallow depressions of a few inches to 20 ft with steep sides. The width and length of sinks range from a few inches to more than 20 ft. Sinks were grouped by size, shape, and steepness of their side slopes (table 1). About 30 percent of the sinks are larger than 10 ft in length or width. Almost 60 percent of the sinks are circular (table 1) and about one-third are steep-sided. Some sinks have steep and gently sloping sides. The width of some sinks narrows with depth. Some sinks have coalesced to form larger features that have varied shapes. The trend of linear sinks generally is subparallel to the trend of the flood plain and drainage channels on the flood plain.

Table 1. Morphology of sinks

Size		Side-slope steepness		Shape	
Feet	Number of features	Description	Number of features	Description	Number of features
Less than 10	1,018	Steep	536	Circular	1,018
Approximately 10	221	Shallow depression	1,038	Elongate	312
Greater than 10	516	Gently sloping	39	Linear	35
Total	1,755	Mix	142	Irregular	390

FIELD INVESTIGATIONS OF NEAR-SURFACE MATERIALS

Near-surface investigations were done to see if there is a correlation between soil conditions with the formation of sinks and to identify subsurface voids and cracks that may serve as conduits for the subsurface transport of sediment. The character of near-surface materials was investigated by describing soils in 13 trenches, analyzing soil samples from the trenches, and conducting electromagnetic and ground-penetrating radar surveys. Thirteen trenches were dug by backhoe to a maximum depth of 19 ft. Eight trenches (2, 3, 4, 6, 9, 14, 15, and 16B) were dug at active sinks; whereas four trenches (5, 8, 13, and 17) were dug in areas without sinks. Another trench (16A) was dug next to a depression thought to be an old, partially filled sink. The trenches were excavated in two phases to allow for evaluation of field procedures used during Phase 1 and modification to improve procedures for Phase 2. Electromagnetic and ground-penetrating radar methods were evaluated for their ability to identify areas with sinks and to locate subsurface voids.

Several distinct soil layers were identified in the trenches. Layers ranged in texture from clay to coarse sand and generally were less than 6.5 ft thick. Soil samples from 13 trenches were analyzed by the BOR for clay mineralogy, moisture content, organic content, particle-size distribution, and dispersivity.

Samples from the clayey layers in the trenches were analyzed for clay mineralogy in the laboratory. The predominant clay mineral was smectite of the calcium montmorillonite variety, which ranged from trace amounts to 65 percent by volume. Illite ranged from trace amounts to 10 percent by volume. Kaolinite was present in trace amounts. Feldspar was the predominant nonclay mineral and ranged from 15 to 70 percent by volume. Clays below 6.5 ft commonly were characterized as dispersive on the basis of the crumb tests (James Swapp, Materials Engineer Specialist, BOR, written commun., 1995). Dispersive clays were not found in the upper 6.5 ft of sediments but could have been removed by percolating water.

The lithology of the upper 16 ft penetrated by the trenches is different in areas with sinks than in areas without sinks. Several layers were identified in each trench but can be generalized into three layers. The uppermost layer generally is 3 to 6.5 ft of clay and silt that typically had a platy structure in the upper part and a laminated structure in the lower part. In areas with sinks, the upper layer sometimes thickened from inches to several feet directly below sinks. The middle layer is 3 to 13 ft thick and in some cases extends to the bottom of trenches. Lithology of the middie layer is distinctly different in areas with sinks than in areas without sinks. In areas with sinks, the middle layer includes several thin layers of various textures but generally can be characterized as a heterogeneous clay and silt with sand stringers. In areas without sinks, the middle layer is dominated by layers of sand that range from 3 to 13 ft thick, and probably represents a paleochannel. Thin layers of silt and clay of uniform thickness are sometimes present in this layer. The lowermost layer in trenches that fully penetrated the middle layer is massive clay.

Subsurface voids ranging in size from inches to several feet in diameter often were found below and near sinks in the two upper layers. Voids were not found below about 6.5 ft. Orientations of the voids appeared to be random. Medium to coarse-grained and moderately to poorly sorted sand lenses of less than 1 ft thickness were found near or immediately below the bottoms of several sinks and voids. Small diameter (<0.1 in.) root casts were common in silt- and clay-rich sediments.

Near-vertical veins of clay and silt were found in four trenches dug at sinks during the second phase of trenching. These veins extended from the bottoms of sinks to at least 6.5 ft below the land surface; a vein found below a sinkhole in Trench 16B extended to at least 11.5 ft below the land surface. Similar veins may have been in trenches dug during the first phase but were not detected. Veins extended beneath a linear trend of small sinks parallel to the long axis of the sinks. Open voids and sand-filled voids were found along the veins in the upper 6.5 ft. Thickening of shallow layers was common near the veins and below sinks indicating that depressions may have existed before or during deposition of the shallow layers. Veins commonly splayed upwards into multiple veins near the bottom of sinks forming a funnel structure similar to prehistoric near-surface subsidence cracks found in alluvial deposits in California (Bull, 1972). Moisture and organic content of the veins were similar to moisture and organic content found in the surrounding soil matrix.

Open cracks were found only in Trench 8, 130 ft west of the Santa Cruz riverbank in an area of few sinks. This crack is probably related to instability of the incised riverbank.

Electromagnetic surveys traversed several sinks and trench sites. The surveys indicated that areas with sinks generally had higher values of electrical conductivity than areas without sinks. Relatively high apparent electrical conductivities (20 to 100 mmhos/m) were found in areas where sinks are prevalent in comparison to uniformly low values (20 mmhos/m or less) in areas where sinks are absent. The high conductivities in sink areas appear to be related to greater clay and moisture content on the basis of data from trenching.

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer

Electrical conductivity is given in millimhos per meter (mmhos/m), which is equal to millisiemens per meter (mS/m).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

INVESTIGATION OF THE CAUSES OF SINKS IN THE SAN XAVIER DISTRICT, TOHONO O'ODHAM NATION, PIMA COUNTY ARIZONA

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